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MAGNETIC FIELD SENSITIVITY OF THE COULOMB ANOMALY IN THE CONDUCTANCE OF A PHASE-COHERENT DISORDERED 2-DIMENSIONAL ELECTRON GAS

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Abstract—We have studied the Coulomb anomaly in the conductance of a phase-coherent disordered 2-dimensional electron gas. Its average magnitude of $\delta G_{\text{EEI}} \approx -0.3\, e^2/h$ is obtained by applying a bias voltage to suppress the Coulomb anomaly. This Coulomb anomaly is suppressed by a parallel magnetic field in contrast to theoretical predictions. Surprisingly, the magnitude of this Coulomb anomaly exhibits reproducible fluctuations in perpendicular magnetic fields on a magnetic field scale much larger than that for universal conductance fluctuations.

Phase-coherent electron transport in disordered conductors gives rise to three mesoscopic conductance contributions with a magnitude of e^2/h: universal conductance fluctuations (UCF), weak localization (WL), and the Coulomb anomaly due to electron–electron interactions (EEI). Both UCF and WL, where electrons are considered as non-interacting particles, have been thoroughly investigated[1]. The Coulomb anomaly arises by including Coulomb scattering between electrons[2–4] and has drawn much less attention over the past years. An attempt towards a qualitative transparent physical understanding[5] starts with the interference of a partial electron wave on a closed path with itself. This charge density pattern (analogous to Friedel oscillations) incorporates dynamical as well as Aharonov–Bohm phases. A second partial electron wave travelling on the same closed path returns coherently after Coulomb scattering from this charge pattern. The resulting reduction in conductance can be expressed as $\delta G_{\text{EEI}} \approx e^2/h(g_F - g_H)$ at zero energy (for 1D EEI). The magnitude of the parallel-spin (exchange) Fock coupling constant g_F is universal and is thus independent of screening. In contrast, the Hartree coupling constant g_H reaches a maximum for perfect screening ($g_H \leq g_F$). Furthermore, g_F and g_H can be subdivided into a diffusion and a cooperon contribution due to two electrons travelling along the closed path in the same or opposite direction respectively. The cooperon contributions are destroyed by a magnetic flux of h/e similarly as WL, whereas the diffusion contributions are predicted to be *insensitive* to a (perpendicular) magnetic flux.

In the presence of a parallel magnetic field, spin-up electrons are Zeeman splitted from the spin-down electrons, which is accompanied by an increase (decrease) in wavelength of the highest occupied spin-up (spin-down) electron. The (exchange) Fock and parallel-spin Hartree contribution are not affected by a Zeeman splitting. Only the anti-parallel spin Hartree contribution is expected to be reduced[6–8] when the Zeeman energy $E_Z \equiv g\mu_B B$ exceeds the Thouless energy $E_T \equiv \sqrt{\hbar D/L^2}$, where L denotes the length of the conductor and D the diffusion constant. Therefore, a parallel magnetic field is predicted to enhance the magnitude of the Coulomb anomaly, which results in a *positive* magnetoresistance[6–8].

Experimentally, the Coulomb anomaly has been observed in the conductance via its temperature dependence[9–12]. Another direct manifestation was the observation of a negative parabolic magnetoresistance[13–15] due to the presence of a magnetic field insensitive diffusion contribution of the Coulomb anomaly in the conductance. These conductors were macroscopic in at least one dimension in order to suppress UCF by ensemble averaging.

A positive magnetoresistance in parallel field was observed in P-doped Si and Si MOSFETs[16–18]. However, the magnitude of this conductance correction was much larger than e^2/h, which increases when the metal–insulator transition was approached. Recently, it has been shown that a parallel magnetic field drives the conducting phase in Si MOSFETs into the insulating state[19–21]. This requests a reinterpretation of the observations reported in Ref.[16–18]. The magnetoresistance of a macroscopic GaAs/AlGaAs 2-dimensional electron gas (2DEG) was studied by Lin *et al.*[15] in both perpendicular and parallel field. Although the Coulomb anomaly was clearly present, they observed a *negative* (temperature-dependent) magnetoresistance in parallel field. This apparent contradiction with the theoretical expectation led these authors to disregard the Coulomb interaction effect as an explanation.

In this paper, we investigate the Coulomb anomaly in the conductance of a *phase-coherent* disordered 2DEG fitted with an overall gate. First, the Coulomb anomaly is identified by applying a bias voltage to suppress all phase-coherent contributions and its magnitude corresponds to a reduction in conductance of about $\delta G_{EEI} \approx 0.3\, e^2/h$. Second, we explicitly study its magnitude in parallel magnetic fields, where the two spin subbands become Zeeman splitted. Third, we check how insensitive its magnitude is to perpendicular magnetic fields.

The 2DEG is present in an InAs/AlSb quantum well. Prior to processing, the top barrier has been removed by wet chemical etching. The 15 nm thick exposed InAs layer hosts the 2DEG with an electron density $n_s \approx 1.5 \times 10^{16}\,\mathrm{m}^{-2}$ and an electron mean free path $l_e \approx 0.2\,\mu$m. The cross-shaped pattern in the InAs-layer was defined by insulating trenches using e-beam lithography and wet chemical etching. Note that its length $L \approx 2.1\,\mu$m and width $W \approx 0.35\,\mu$m are larger than l_e, which implies that transport is diffusive. After taking scanning electron micrographs (Fig. 1), a 65 nm SiO_2 layer (PECVD) and a 40 nm Ti/Au electrode are deposited. The Ti/Au electrode covers the entire area displayed in Fig. 1.

We have studied four nominally identical devices at low temperatures. The differential resistance $R_{16,25}$ is measured by applying an AC (and DC) current between terminals 1 and 6 and measure the AC voltage between terminal 2 and 5 with a lock-in technique. The gate-voltage is applied with reference to one of the terminals connected to the 2DEG. The resulting gate-voltage dependence of $R_{16,25}$ is plotted in the insert of Fig. 2(a). Depletion occurs at a gate-voltage of about -5.5 V. For negative gate-voltages only the first 2D-subband of the 2DEG is populated. The Hall resistance $R_{16,74}$ measured in a perpendicular magnetic field of 1 T showed that the electron density depends linearly on gate-voltage (not displayed).

The differential resistance $R_{16,25}$ at 140 mK is displayed in Fig. 2(a) vs DC bias voltage. The zero-bias resistance is clearly enhanced compared to high bias, which will be shown to be the Coulomb anomaly. The high-bias resistance is equal to its

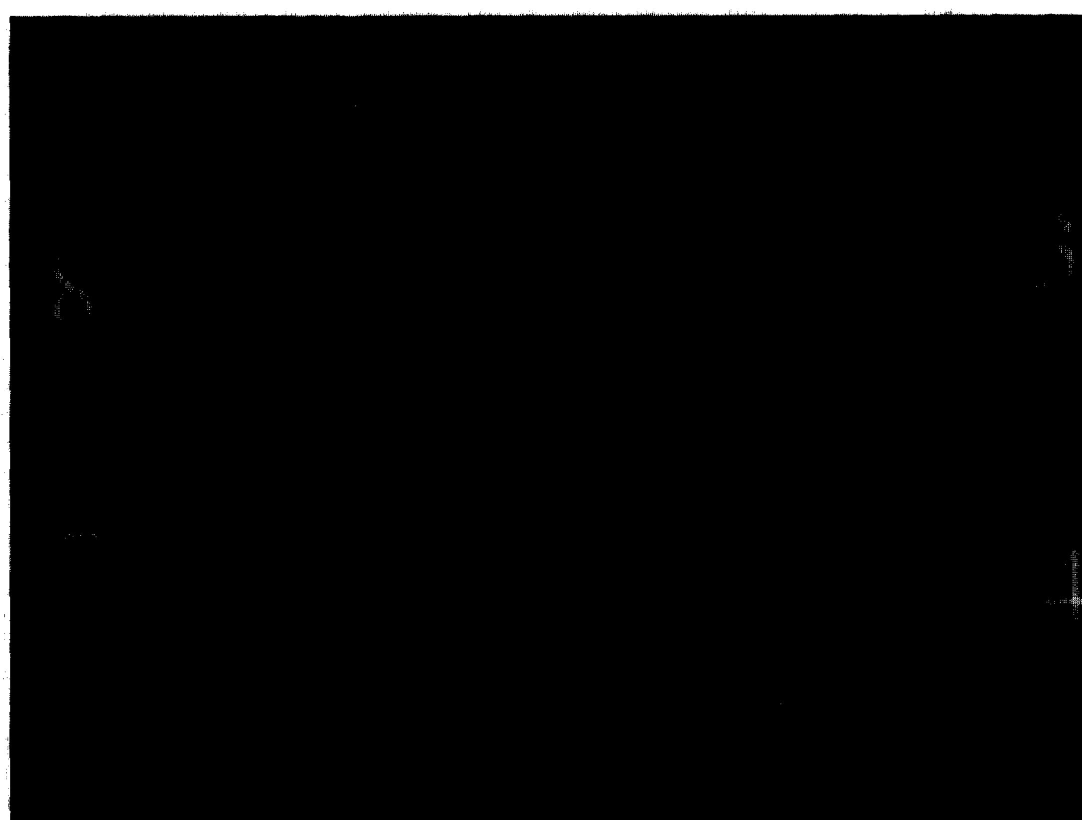

Fig. 1. Scanning electron micrograph of the disordered cross-shaped 2DEG before depositing the gate-electrode. The darker regions represent insulating trenches in the 2DEG.

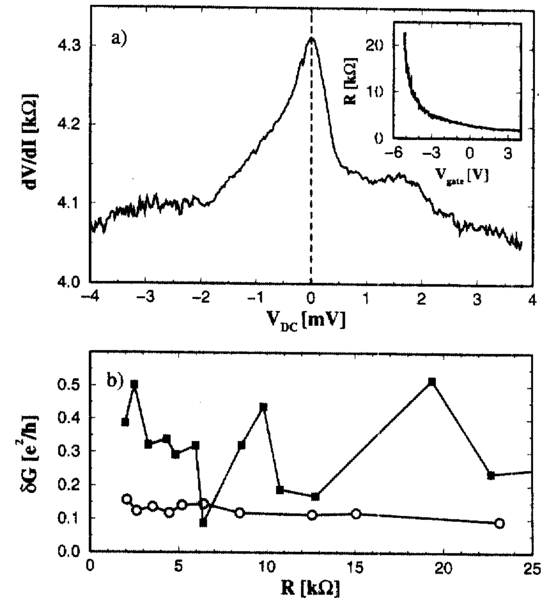

Fig. 2. Panel (a) shows the differential resistance $R_{16,25}$ vs applied DC bias voltage measured at $V_{gate} = -1.5$ V, $T = 140$ mK, and a perpendicular magnetic field of 1 T. The inset shows the resistance $R_{16,25}$ at zero bias vs gate voltage. The filled squares displayed in panel (b) represent the magnitude of the reduction in zero-bias conductance compared to high-bias (±3 mV) voltage vs its zero-bias resistance $R_{16,25}$. The open circles denotes the rms magnitude of the (universal) magnetoconductance fluctuations obtained over a magnetic field range between 0.5 to 4.5 T.

classical Drude value, since all phase-coherent contributions are suppressed*. The phase-coherent resistance correction can be obtained by determining the difference between the zero-bias and high-bias resistance. The resulting contribution to the conductance is plotted in Fig. 2(b) as a function of the resistance by changing the gate-voltage. We corrected for a linear dependence of the classical resistance at high-bias voltage by extrapolation to zero bias, which yields an average classical zero-bias resistance. Note that the contribution due to WL is suppressed by applying a perpendicular magnetic field (1 T) much larger than one flux quantum h/e. Since for all gate-voltages a reduction in zero-bias conductance is observed with an (average) magnitude $\delta G_{EEI} \approx 0.3\, e^2/h$, we have unambiguously identified the Coulomb anomaly. The observed deviations from its average magnitude corresponds to the contribution due to UCF, which is present at zero bias. The rms magnitude of UCF is plotted in Fig. 2(b), which shows a gate-voltage independent magnitude of $\delta G_{UCF} \approx 0.13\, e^2/h$.

After having characterized the Coulomb anomaly in our phase-coherent conductor, we continue by investigating its parallel magnetic field dependence. The bias-voltage dependence of the differential resistance $R_{16,25}$ at 1.7 K is plotted in Fig. 3(a) for increasing magnetic fields applied to a 13° tilted device. The Coulomb anomaly at $B_{parallel} = 0$ is visible around zero bias. For increasing magnetic fields this Coulomb anomaly disappears instead of showing the predicted enhancement. In panel Fig. 3(b), the zero-bias resistance is plotted vs parallel magnetic field, which exhibits a *negative magnetoresistance*. Comparison with the classical resistance reveals that the Coulomb anomaly is destroyed around a magnetic field of 7 T. A conservative estimation for the Zeeman energy at 7 T is about $E_Z \approx 1.6$ meV ($\gg k_B T \approx 0.15$ meV) using a Landè g-factor of -4[22,23], which corresponds to an applied bias voltage where the Coulomb anomaly is substantially suppressed.

The data presented in Fig. 3 does not exclude the cooperon contribution to the Coulomb anomaly. From the slope in the Hall resistance, we deduced that the device was rotated by about 13°. However, we exclude the trivial suppression of a cooperon contribution due to a perpendicular component of the magnetic field for two reasons. First, we observed that the (average) magnitude of the Coulomb anomaly did not vary significantly by applying a perpendicular magnetic flux much larger than h/e (Fig. 1(a)). Second, the magnetoresistance in perpendicular field (see Fig. 4(a) does not exhibit

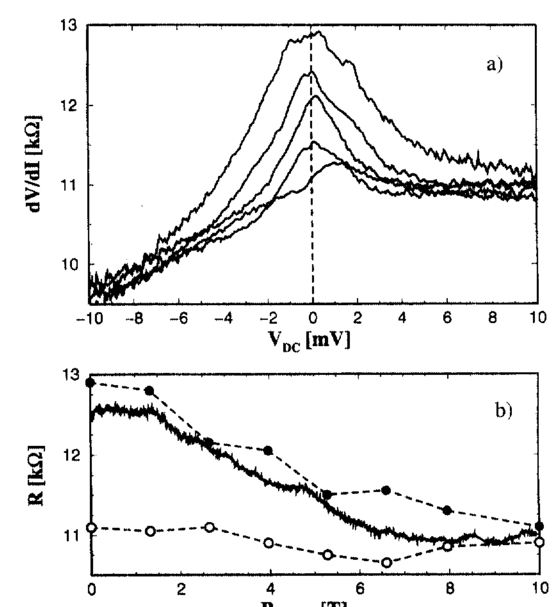

Fig. 3. Panel (a) displays $R_{16,25}$ vs DC bias voltage measured at fixed parallel magnetic fields: from top to bottom 0, 2.5, 4, 5.5, and 10 T, with $V_{gate} = -4.0$ V and $T = 1.7$ K. Panel (b) shows the zero-bias magnetoresistance vs parallel magnetic field (solid line). The circles represent the resistance determined at zero bias (filled) and at high bias (open) from I–V-curves as displayed in panel (a).

*The UCF at these high bias voltages was suppressed, which implies that the phase-breaking length was reduced due to inelastic scattering.

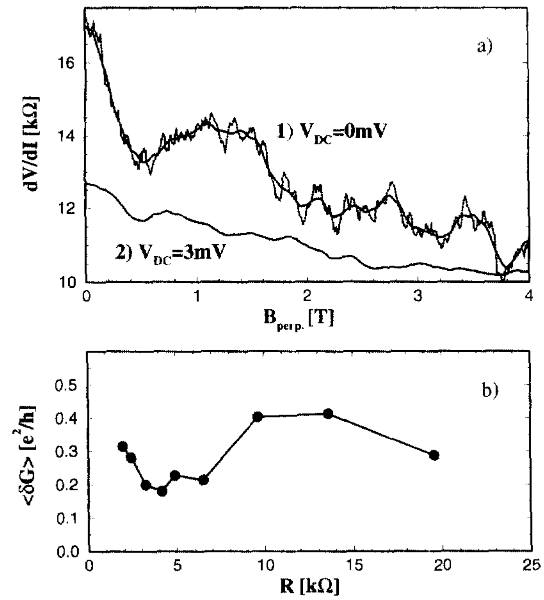

Fig. 4. Panel (a) displays the magnetoresistance $R_{16,25}$ in perpendicular magnetic field at $V_{gate} = -4.7$ V and $T = 180$ mK. The dashed line (1) displays the zero-bias resistance which exhibits UCF. The solid lines (1) and (2) display the resistance averaged over $\Delta B = 0.2$ T for a bias voltage of 0 and 3 mV respectively. Note that the Coulomb anomaly in the resistance is equal to the difference between the two solid lines. In panel (b) the averaged magnitude of the Coulomb anomaly in the conductance obtained from a magnetic field interval between 0 and 2.5 T is plotted vs the zero-bias resistance $R_{16,25}$.

a clear signature of weak (anti-)localization. This implies that cooperon contributions are negligible. Therefore, we conclude that the data of Fig. 3 shows that the diffusion contribution to the Coulomb anomaly is destroyed by the Zeeman energy, which is in apparent conflict with theoretical predictions.

Recently, a reduction has been observed in the tunneling density of states at the Zeeman energy[24]. Similarly, also a Coulomb anomaly should appear in the conductance at voltages equal to the Zeeman energy, which was actually the original motivation to study its dependence in parallel magnetic fields. However, these Zeeman Coulomb anomalies are not present in our devices as can be verified in Fig. 3(a).

The striking parallel magnetic field dependence of the Coulomb anomaly motivated us to thoroughly study its sensitivity to a perpendicular magnetic field. The presence of Subnikov–de Haas oscillations in high magnetic fields limits us to magnetic fields below about 4 T. We have plotted in Fig. 4(a) the magnetoresistance measured at 180 mK both at zero bias and at a bias of 3 mV, which are reproducible. We checked that a bias of 3 mV the Coulomb anomaly was almost completely suppressed; compare e.g. with Fig. 2(a). The magnetic field sensitivity of UCF is about $B_c \approx 25$ mT. Therefore, UCF can be suppressed by averaging over 0.2 T. The dotted line in panel (a) measured at zero bias represents the magnetoresistance without averaging, which still exhibits UCF. Note that the UCF contribution is predicted to be unaffected by EEI[25]. The difference between the two solid lines in panel (a) thus directly reflects the magnitude of the Coulomb anomaly. Its gradual reduction by a perpendicular magnetic field can be attributed to the Zeeman splitting.

Surprisingly, the magnitude of the Coulomb anomaly exhibits strong fluctuations over a magnetic field scale of about 1 T. This fluctuating magnitude of the Coulomb anomaly was observed for all applied gate-voltages. Moreover, the average magnitude of the Coulomb anomaly between 0 and 2.5 T determined at several gate-voltages shows a variation of about 50% (panel b). Note that although EEI remain short ranged, one could expect a small increase of the Coulomb anomaly when the resistance increases, since the screening becomes less effective. We conclude that the magnitude of the Coulomb anomaly in the conductance of a *phase-coherent* disordered conductor is *sensitive* to a perpendicular magnetic flux.

In discussion, the observed suppression of the Coulomb anomaly by a parallel magnetic field sheds new light on other experiments. First, we suggest that the observed negative magnetoresistance in parallel fields by Lin *et al.*[15] is caused by a suppression of the Coulomb anomaly of $\delta G_{EEI} \approx -0.8\, e^2/h$ due to Zeeman splitting. Second, the parabolic negative magnetoresistance in perpendicular magnetic fields originates from a field-independent conductance correction. In contrast to 2D (macroscopic) conductors, the negative magnetoresistance for 1D (macroscopic) conductors exhibited a linear negative magnetoresistance[13,14], which could be related to a gradual suppression of the Coulomb anomaly due to the Zeeman splitting. Third, the sawtooth-shaped Subnikov–de Haas oscillations observed in the longitudinal magnetoresistance of a 1D GaAs/AlGaAs 2DEG were suggested to be related to the oscillating g-factor[26]. We remark that this oscillating g-factor could result in an oscillating (parabolic or linear) negative magnetoresistance contribution, since the Coulomb anomaly will be suppressed by an oscillating Zeeman splitting.

In conclusion, we have studied the Coulomb anomaly in the conductance of a cross-shaped phase-coherent disordered 2DEG. The Coulomb anomaly is shown to be suppressed by a parallel magnetic field. In perpendicular magnetic fields, the Coulomb anomaly exhibits reproducible variations in magnitude. Both observations are in conflict with present theoretical predictions.

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